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The demonstration and simulation of the application performance of the vanadium dioxide single glazing

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ABSTRACT

As a typical thermochromic material, the vanadium dioxide (VO_2) has a great potential for building energy efficiency development. In this study, the VO_2 glazing's application performance was first demonstrated in full-size, and simulated with a software of high credibility. For a 2.9 m × 1.8 m × 1.8 m low-mass room whose window's size is 1.65 m × 1.65 m, the measured results showed that the room with the VO_2 glazing saved 10.2–19.9% cumulative cooling load than that with an ordinary glazing during the demonstration. The application performance to a conventional residential room in the hot summer and warm winter zone was simulated in BuildingEnergy, a simulation software developed by the authors. The simulated results showed that the use of the VO_2 glazing could save ~9.4% electricity consumption. The effects of the window's orientation and the area ratio of window to wall were also discussed in this study.

1. Introduction

The building energy consumption corresponds to 30–40% of the primary energy used in the developed countries [1]. And the ratio in China was 23% in 2007 and 2008, and is still increasing [2]. The main building energy consumption contains the energy for construction, operation and rehabilitation of the building. And the operating energy, which used predominantly for space cooling/heating, ventilation, lighting and other electrical appliances, plays a dominant role [3]. Due to its worst thermal insulation performance among the building envelopes, the window has a great potential for energy efficient development. As a widely studied advanced window, chromogenic window can change its spectral properties triggered by an external stimulus [4]. The chromogenic technologies [5] extensively researched involve electrochromic [6], photochromic [7], thermochromic [8] and gasochromic technologies [9]. And the thermochromic windows, whose properties's transition depends on the temperature, are relatively low-cost compared with others.

Vanadium dioxide (VO_2) is the most investigated thermochromic material, which was first reported in 1959 [10]. The material is able to undergo a reversible transition at a phase transition temperature (T_τ): when the temperature is lower than T_τ, it is monoclinic, semiconducting and rather infrared transparent; and when the temperature is higher than T_τ, it is tetragonal, metallic and infrared reflecting. However, the VO_2's application to building energy efficiency is blocked by three problems: first, the bulk VO_2's T_τ, which is ~68 °C, is too high; second, the VO_2's luminous transmittance, which is ~50% or less, is too low; third, the modulation of the solar energy throughput between the VO_2's two states is modest [11]. For the first problem, doping with transition metal ions can lower T_τ significantly. The most widely investigated dopant is tungsten, with which the VO_2's T_τ can be brought to the room temperature range [12]. VO_2 films with T_τ of 30.0 °C and 38.5 °C were reported in the reference [13] and [14], respectively. For the second problem, multi-layer structure is adopted to improve the VO_2 coating's luminous transmittance [1,5]. And the VO_2 film with improved solar energy modulation has been prepared [15,16].

Besides the studies on the improvement of VO_2's properties, how to demonstrate the VO_2's application performance to the building is also discussed. Gao et al. have tested the applied properties of different types of VO_2 films in two model houses of 34 cm × 27 cm × 29 cm [17]. Saeli et al. have used the Energy Plus software to simulate the energy consumption of the rooms with thermochromic windows [18,19]. In this study, we present the experiment results of a single VO_2 glazing applied to a room that

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has a real room's size, and the simulation results of the glazing applied to a residential room. According to the conclusions given in [18,19] and our previous work [20], the VO_2 glazing is not applicable in cold climate regions due to its low solar transmittance, which decreases the indoor air's heat gain from the solar radiation and leads to an increase in heating energy consumption. Therefore, the VO_2 glazing's application performance for lowering the cooling load in hot climate region is discussed here. Based on these results, the VO_2's effect on building energy efficiency is elucidated.

2. Performance demonstrations of a single VO_2 glazing applied to a low-mass room

We designed and manufactured a type of thermal-stable PET film covered with VO_2 (shown in Fig. 1). A VO_2 glazing can be formed conveniently by sticking the film on an ordinary glass substrate. As shown in Fig. 1, the film's color, which was yellowish, may be unfavorable and could be modulated by the integration of noble metals [19]. The phase transition temperature of the VO_2 particles on the film is 41.3 °C, and the film's spectral transmittance at low temperature (in its semiconductor state) and high temperature (in its metal state) are shown in Fig. 2. The noise between 2000 and 2500 nm is caused by the absorption of the PET film.

Fig. 1. Thermal-stable PET film covered with VO_2.

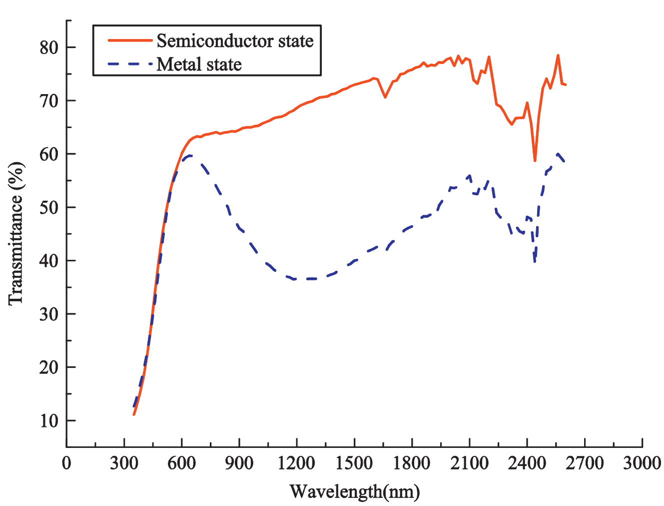

Fig. 2. Spectral transmittance of VO_2 film in the semiconductor state and metal state.

To demonstrate the application performance of the VO_2 glazing, we established a Testing and Demonstration Platform for Building Energy Research in Hefei, China. The platform is located at the roof of a six-floor building to keep away from the surrounding buildings' shadows, and its schematic diagram is shown in Fig. 3. The platform contains two identical testing rooms: Room A and Room B. During the demonstration, one room can be set as an experiment unit by adopting a building component or material that needs to be demonstrated, while the other one can be set as a control. The testing rooms are 2.9 m in length, 1.8 m in width and 1.8 m in height. The south walls of the rooms are glass curtain walls, and the glass on which has a size of 1.65m × 1.65m. The non-transparent envelopes of the rooms are made of polyurethane wrapped with metal boards, and the polyurethane is 37 kg/m^3 in density, 1385 J/(kg K) in specific heat and 0.0228 W/(m K) in thermal conductivity. The thicknesses of the walls and the roofs are 10 cm. As mentioned, the testing rooms are located above the building's top-floor rooms, while the top-floor rooms' thermal environment may not be the same. Difference in the thermal environment will lead to a difference in heat transfer between the top-floor rooms and the testing rooms through the building's roof, which may make the testing rooms exposed to different external conditions. To weaken the effect of the heat transfer through the building's roof, the testing rooms are suspended above the roof by putting on two steel frames, and their floors are thickened to 15 cm. There are no heat sources in the rooms. The indoor temperature of the rooms can be maintained at a particular temperature through the input of cool/heat wind from the fan coil units. The load that is needed to maintain the indoor temperature can be calculated using the equation below:

$$q = c_{water}\dot{m}(T_{out} - T_{in}) \quad (1)$$

where c_{water} is the specific heat of the water in the coil, whose value is 4200 J/(kg K); $\dot{m}$ is the mass flow rate of the water; T_{out} and T_{in} are the water temperatures at the coil's outlet and inlet, respectively.

During the demonstrations, the VO_2 film was pasted on the southern window of Room A, and Room B was set as the control whose window had only an ordinary glazing. The photos of these two testing rooms are shown in Fig. 4. The radiation properties of the ordinary glazing and the VO_2 glazing are listed in Table 1.

The demonstration began on July 7th, 2012 and lasted for 7 days. The indoor temperatures of the testing rooms were set to 20 °C. The variations in the rooms' cooling load are shown in Fig. 5, which shows that the cooling load of Room B was greater than that of Room A. This is the result of the VO_2 glazing's lower solar transmittance in the both metal and semiconductor states compared with that of the ordinary glazing. The lower solar

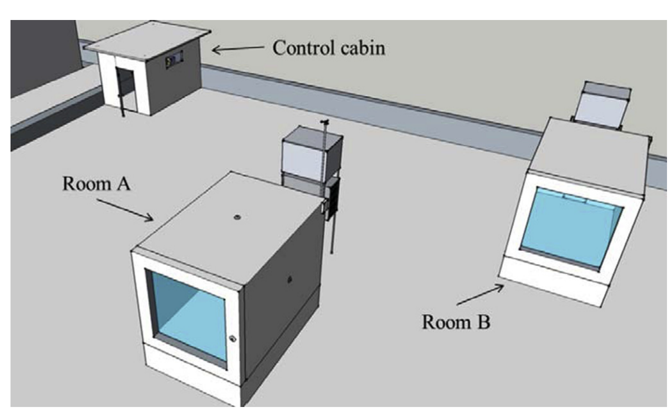

Fig. 3. Schematic diagram of the Testing and Demonstration Platform for Building Energy Research.